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ANNUAL REPORT

RESEARCH IN THE OPTICAL SCIENCES

F49620-80-C-0022

Contract [redacted]

October 1, 1979, through September 30, 1980

Submitted to

Air Force Office of Scientific Research

Bolling Air Force Base

Washington D.C.

by

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721
Peter A. Franken, Director

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INTRODUCTION

This annual report to the Air Force Office of Scientific Research under contract F49620-80-C-0022 describes work accomplished from October 1, 1979, through September 30, 1980, by personnel of the Optical Sciences Center.

On the following pages we discuss the objectives of each task, the progress made under that task, written publications and interactions resulting from the work, professional personnel and students associated with the individual research efforts, degrees obtained through work on the tasks, and consultative and advisory functions to other laboratories and agencies.

TWO-DIMENSIONAL PHENOMENA AT SURFACES UNDER HIGH ELECTROMAGNETIC FLUX

(A. B. Meinel, R. Zito)

Objective

The objective of this two-year study, begun this year, has been to evaluate the relative merits of reflective thin films materials useful in solar energy technology, as mirrors for laser weapons, and as protective coatings in laser warfare. Three phases of the study were considered:

1. Laboratory tests of film failure at high temperatures (to provide an estimate of temperatures and therefore fluxes needed for the in-flux tests of phase 3.

2. Passivation studies.

3. In-flux tests.

Progress

Phase 1 of the objective has been completed. Although originally we intended to study only the soft reflecting metals Al, Cu, Ag, and Au, we extended our study to include Ni, Cr, Rh, Pt, W, and Mo. The surface morphological changes of these metals were studied as a function of temperature for 1-hour anneals; such changes included pinhole formation, agglomeration, cracking, peeling, oxidation, recrystallization, and the interdiffusion of atoms across surfaces in multilayer selective surfaces. Tests were carried out in both vacuum and air on various substrates (fused silica, soda-lime glass, silicon wafers) of uniform composition and cleanness.

Of all the metals studied, platinum reflectors seem to be the most durable at high temperatures (and therefore high fluxes) in air. Of the base metals studied, nickel reflectors are most durable at high temperatures in air. In one case, the effect of annealing specimens in He and H_2 was evaluated.

We have developed mathematical tools to enable us to predict the temperatures at which film failure occurs, and these predictions agree well with experiment. We have also uncovered the relationships between various film defects and studied their evolution from film deposition point defects to complete breakup (agglomeration) at high temperatures. In most cases we used materials of exceptional purity, as use of such materials makes it easy to spot trends in the mathematical analysis of test results. A few materials were of industrial quality, as it is interesting, from a practical point of view, to know the failure temperature of these materials; tests on these materials also provided a gauge for determining how well theoretical extrapolations from data on ideal materials may work in the industrial realm, where purity of materials may be sacrificed to produce low-cost, mass-produced products.

We recorded surface features before and after heating by scanning electron microscopy and by both transmission and reflection optical microscopy. Crystal structures were explored by electron and x-ray diffraction. Transmission electron microscopy was used to explore grain size. There is a certain amount of art involved in evaluating surface changes. Frequently we would photograph a characteristic mark, defect, or discoloration in the surrounding metal so that we could return to this characteristic spot after heating.

The failure temperatures presented in the resulting report[1] will provide a ready data reference for estimating the high-temperature performance of the multitude of "stack" selective surfaces (tandem stacks, inverse tandem stacks, interference stacks, etc.) in existence today and planned for the future. The collected data will also be useful in the design of selective stacks since they will indicate when and where stopper layers should be us : in the determination of the thermal durability of electronic components employing metallic coatings; and in the determination of the performance of simple metal coatings used on concentrating and flat-plate mirrors subject to high solar flux and heat, and on military mirrors used for laser weapons.

Phase 2, passivation studies, has also been completed. These studies were originally scheduled for the second year but instead were done in the first year. The temperatures, atmospheres, coefficients of thermal expansion, and conditions of thermal cycling were established that would ensure the integrity of a film or composite stack of films against failure due to cracking, agglomeration, pinhole formation, peeling, oxidation, and interdiffusion into Al_2O_3 overcoatings.

Phase 3, in-flux studies at one of the solar thermal test facilities, was originally scheduled for the first year but has been rescheduled for the second year. We expect these in-flux tests to show slightly lower failure temperatures than those obtained in phases 1 and 2 of this project.

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1. R. R. Zito, "The High Temperature Behavior of Thin Metal Films," PhD Dissertation, University of Arizona, 1980.

Publications and Interactions

R. Zito, "Failure of reflective metal coatings by cracking," Thin Solid Films, to be published.

R. Zito, "Line broadening in x-rays diffracted from thin films," to be submitted to Thin Solid Films.

R. Zito, "The high temperature behavior of platinum films," to be submitted to Thin Solid Films.

R. Zito, "A close look at the agglomeration of gold," to be submitted to Thin Solid Films.

R. Zito, "A comparative study of the behavior of ten metal films at high temperatures in air," in preparation.

R. Zito, "Two-dimensional melting phenomena and surface defects in metallic thin films," paper presented at OSA Topical Meeting on Optical Phenomena Peculiar to Matter of Small Dimensions, Tucson, Arizona, March 18-20, 1980.

R. Zito, "Failure of reflective metal coatings by cracking," paper presented at Second Solar Reflective Materials Workshop, San Francisco, Calif., Feb. 12-14, 1980.

Professional Personnel Associated with This Effort

Aden B. Meinel, Principal Investigator
Richard R. Zito, Co-Principal Investigator
Louis Demer, expert in x-ray methods
Henn Oona, expert in proton induced x-ray analysis

Degrees Awarded

Richard Raymond Zito, PhD (Physics) completed Sept. 12, 1980.
Dissertation title: "The High Temperature Behavior of Thin Metal Films"

SURFACE AND VOLUME SCATTERING OF REFLECTORS AND REFRACTORS

(William L. Wolfe, R. V. Shack)

Objective

To improve the instrumentation and techniques for the measurement of the angular scattering properties of useful materials.

Progress

The manually operated prototype instrument has been used to refine the techniques of making angular scattering measurements in both reflection (BRDF) and transmission (BTDF). Computer programs have been developed and used for calculating and plotting the BRDF and BTDF data.

Measurements were made on gold-coated sandpapers to establish a reference standard for BRDF measurements. Other measurements were made on transmitting samples, which enabled a better understanding to be developed in the use of the partial coherence theory of scattering.

While the manually operated prototype instrument was being employed as described, work continued on the design, development, and construction of the automated scatterometer. This new instrument is at the stage where about 85 percent of its hardware is completed and about 75 percent of the software required for its operation has been developed. The far-infrared laser that was incorporated into the automated instrument has been operated at 118 and 41.7 μm.

Some scattering measurements have been made at 118 μm. Several small separately funded programs have been undertaken to provide various government agencies with the scattering data they require. The performance of the work under these programs and this program has been synergistic, with great advantages accruing to all of the effort.

Some of the accomplishments under the other programs are described under the section entitled "Consultative and Advisory Functions."

Publications and Interactions

Wolfe, W. L., and H. P. Stahl, "Some calculational results using multicolor radiation inversion," presented at OSA Annual Meeting, New York, Oct. 1979; published in Infrared Phys. 20:293-296, Feb. 1980.

Wolfe, W. L., "Effects of reflected background radiation on radiometric temperature measurement," presented at SPIE, Washington, D.C., April 10-11, 1980; published in Proc. SPIE 226, 1980.

Wolfe, W. L., "Comparison of coherent and incoherent imaging in the location of point sources," presented at SPIE, Washington, D.C., April 10-11, 1980; published in Proc. SPIE 226, 1980.

Wolfe, W. L., co-editor of Proc. SPIE 226, 1980.

Bartell, F. O., E. L. Dereniak, and W. L. Wolfe, "The theory and measurement of BRDF and BTDF," presented at SPIE meeting, Huntsville, Ala., Oct. 2, 1980; published in Proc. SPIE 257, 1980.

Brooks, L. D., and W. L. Wolfe, "Microprocessor-based instrumentation for bidirectional reflectance distribution function (BRDF) measurements from visible to far infrared (FIR)," presented at SPIE meeting, Huntsville, Ala., Oct. 2, 1980; submitted to Opt. Eng.

Dereniak, E. L., and T. Stuhlinger, "The use of gold-plated sandpaper as a BRDF standard," presented at SPIE meeting, Huntsville, Ala., Oct. 2, 1980; submitted to Appl. Opt.

Dereniak, E. L., T. W. Stuhlinger, and F. O. Bartell, "Bidirectional reflectance distribution function of gold-plated sandpaper," presented at SPIE meeting, Huntsville, Ala., Oct. 2, 1980; published in Proc. SPIE 257, 1980.

Fender, J. S., "Stray radiation analysis programs (GUERAP III-APART/PADE): A user's viewpoint," presented at SPIE meeting, Huntsville, Ala., Oct. 2, 1980; published in Proc. SPIE 257, 1980.

Wolfe, W. L., "Scattered thoughts on baffling problems," presented at SPIE meeting, Huntsville, Ala., Oct. 2, 1980; published in Proc. SPIE 257, 1980

Bartell, F. O., E. L. Dereniak, and W. L. Wolfe, "BRDF and BTDF measurement considerations," presented at annual meeting of Optical Society of America, Chicago, Ill., Oct. 15, 1980; submitted to Applied Optics.

Wolfe, W. L., and H. P. Stahl, "Three-color radiometric temperature determinations," presented at annual meeting of Optical Society of America, Chicago, Ill., Oct. 15, 1980; submitted to Applied Optics.

Baltes, H. P., and W. L. Wolfe, "K-correlations and facet models in diffuse scattering--experimental evaluation," submitted to Optics Letters.

Professional Personnel Associated with This Effort

William L. Wolfe, Professor
Eustace L. Dereniak, Assistant Professor
Frederick O. Bartell, Research Associate
Steven Lange, Research Associate
Lawrence D. Brooks, Student
Janet S. Fender, Student
Sungmuk Lee, Student
Tillman Stuhlinger, Student
Yaujen Wang, Student

Degrees Awarded

Janet S. Fender, PhD (Optics), 1981
Dissertation title: "An Investigation of Computer-Assisted Stray Radiation Analysis Programs"

Lawrence D. Brooks, PhD (Optics), expected 1981
Projected dissertation title: A Microprocessor-Based Multi-Spectral Scatterometer"

Tillman Stuhlinger, MS (Optics), expected 1981

Consultative and Advisory Functions

Using the techniques and instruments that have been improved under the program, we have made specific measurements and calculations, under separate funding, to further various military and space programs. These are described below.

Under a contract with the U.S. Army Materials and Mechanics Research Command at Watertown, Mass., under the monitorship of Dr. Anton Hofmann, we have made a determination of the surface and bulk scattering of ZnSe windows in the visible and the infrared. We have provided BRDF data in the infrared on series of special blacks by way of a subcontract with the Breault Research Organization and Gruman Aircraft to an undisclosed military sponsor.

We have consulted with Eugene Church at IRADCOM at Picattiny, New Jersey, on the comparison of scattering theory and BRDF measurements.

Under separate contract we have provided infrared scattering and baffling design data to the Army BMDATC for its Forward Acquisition System (FAS).

Under a recently completed subcontract with Science Applications, Inc., we have provided Major Seid at USAF SAMSO with infrared BRDF data and scattering and off-axis rejection design data for the Deep Space Surveillance System (DS^3). We have recently completed a contract with the Navy's David Taylor Research Center wherein we provide them with the visible and infrared scattering characteristics of various types of Navy paints.

We are presently working on our second contract with Vought Corporation Advanced Technology Center, wherein we are investigating the infrared scattering properties of phase change films.

We have worked on a subcontract from Aerojet wherein we determined the effect of a nuclear radiation exposure on the scattering properties of zinc selenide windows. We have also provided BRDF data, design changes, and APART scattering calculations to Dr. Harold Bennett under a small Naval Weapons Center contract, which may greatly increase the acquisition range of one of that center's missiles.

LIGHT SCATTERING FROM REFLECTIVE OPTICAL SURFACES

(R. V. Shack, D. Thomas)

Objective

The primary goal of this study was to examine experimentally the particle contaminant contribution to the scattering of visible light from front-surface mirrors.

Progress

The objective was achieved through the dissertation research work of Dr. Thomas (see Degrees Awarded, below). Excepts from his dissertation abstract are as follows:

[The contribution of particle contaminants to scattering of light] can be significant even for carefully prepared and handled mirrors, and . . . surface particulate scatter can qualitatively explain discrepancies that have been observed by other authors between the shapes of measured scattering profiles and those of profiles predicted for scattering from smooth surface microroughness. Scattered light distributions are also recorded and discussed for several diffuse reflectors.

A careful description is given of the operation and limitations of a device used to measure the angular distribution of light scattered from nominally flat, reflecting optical surfaces. The sample illumination angle and polarization of the incident beam can both be varied with this instrument, and orthogonal polarization components of the scattered light can be independently measured.

The scattering levels of most of the studied mirrors are shown to be in good agreement with their photographically recorded degree of particulate contamination. The shapes of the scattering profiles measured for a few of the samples are also in general agreement with the overall sizes of their particulate contaminants. Further insight into the nature of surface particulate scattering is derived from several experiments involving deliberately altered or contaminated samples.

The polarization state of light scattered from both smooth and rough reflecting surfaces is experimentally determined and discussed. Results obtained for the smooth samples are shown to be qualitatively explained by a simple model for scattering from surface particulates. Invariance properties are also empirically determined for the scattered light profiles of several samples.

Professional Personnel Associated with This Effort

Roland V. Shack, Professor
William L. Wolfe, Professor
David A. Thomas, Graduate Student

NEW APPROACH TO OPTICAL PROCESSING

(H. H. Barrett, A. F. Gmitro)

Objectives

1. To operate an image orthicon TV camera in an unusual bipolar mode, in which either a positive or negative charge can accumulate on the target.

2. To use this bipolar mode as the basis for synchronous demodulation of a modulated light beam.

3. To use the orthicon in conjunction with a photoelastic modulator in the pupil plane of a lens as a general-purpose noncoherent optical processing system.

Progress

We have achieved the first two objectives stated above. We have shown that the camera can be operated in an abnormal region where negative charge rather than positive charge accumulates on the target. We have demonstrated this and the synchronous demodulation capability afforded by this phenomenon by means of several experiments:

(1) Using an array of LEDs, we modulated several in the array and left the others running continuously. We applied the synchronous modulation signal to the camera, on top of a variable bias. This combined signal was the photocathode-to-target accelerating voltage. We observed that at high bias all the LEDs were visible in the image as expected. As we lowered the bias voltage toward the $\delta = 1$ condition

(that is, voltage for which we get a single secondary electron per incident photoelectron), we observed that the entire image dimmed but that the lights operated strictly dc dimmed faster until, at the $\delta = 1$ point, they disappeared altogether, leaving only the modulated LEDs visible. This experiment verifies that we indeed have a negative charge cancellation of the positive charge and that we can use this fact to synchronously demodulate a modulated signal.

(2) We have done similar experiments with a spinning mesh (chopper), where we derive a reference signal from the chopper and use this to synchronously demodulate the chopper rotation.

(3) We have also demonstrated the modulation/demodulation process with the photoelastic modulator. We used the photoelastic modulator to modulate part of an input scene and, by means of the camera, demodulated the scene so that only the modulated portion remained visible.

We are currently trying to quantify the performance of the total system as it applies to objective 3. Important considerations are dynamic range and resolution.

Another area of application for this orthicon device is in heterodyne interferometry. We have already demonstrated operation of the camera at about 100 kHz with the LEDs and therefore expect the heterodyne experiments to be straightforward.

Publications and Interactions

H. H. Barrett, A. F. Gmitro, and M. Y. Chiu, "Use of an image orthicon as an array of lock-in amplifiers," Opt. Lett. Nov. 1980.

Presentation of principles and results at Optical Society of America Annual Meeting, Chicago, 1980.

Professional Personnel Associated with This Effort

H. H. Barrett, Professor
A. F. Gmitro
M. Y. Chiu

Invention Disclosure

H. H. Barrett, M. Y. Chiu, and A. F. Gmitro, "Use of an [illegible] [illegible] as an array of lock-in amplifiers," submitted [illegible].

Further Information (Background)

A great deal of effort has been expended in the past [illegible] decades in the area of coherent optical data processing. The well known Fourier transforming properties of lenses make it possible to easily perform any linear shift invariant filtering operation [illegible]. With a little ingenuity, nonlinear and shift variant operations [illegible] performed as well. By operating on a large two-dimensional [illegible] in parallel, the [illegible] systems have the potential of [illegible] speeds. The most important application has been in radar signal processing, especially for synthetic aperture radar.

Nevertheless, coherent optics [illegible] not lived up to its potential, and it is rapidly being supplanted by digital [illegible] applications. We can identify two major impediments to the [illegible] coherent optical processors. First is the difficulty of data [illegible]. In synthetic aperture radar the data are [illegible] photographic transparency that [illegible]. In other applications real time processing is desired and [illegible] photographic film is unacceptable. Light valves such as the [illegible] [illegible] Hughes liquid crystal device are being developed for [illegible] they tend to be slow and have limited spatial resolution. The second impediment is noise. Coherent optical systems are notoriously susceptible to speckle and other forms of noise.

Both of these difficulties can be circumvented through the use of noncoherent optical processors. Any noncoherent light source such as a CRT or an array of light-emitting diodes is a good input medium for noncoherent processing. Furthermore, a recent analysis has shown that noncoherent processors can offer an advantage in signal-to-noise ratio of as much as a factor of 1000 over their coherent counterparts.[1] The drawback to noncoherent systems was once thought to be inflexibility; that is, the class of filter functions that could be implemented seemed to be rather limited. In particular, only positive definite impulse responses are readily attainable. It is now clear, however, that any arbitrary bipolar (or even complex) filter can be implemented either by using two or more parallel optical channels, or by temporally or spatially modulating the properties of a single channel. Temporal modulation of the pupil function of the optical system to synthesize a desired OTF is particularly attractive. We have used this approach in our laboratory with considerable success, but only in systems where the output signal is read out with a single, mechanically scanned detector and demodulated with a lock-in amplifier. A high-speed, parallel-output noncoherent optical processor could be constructed if we had an array of, say, 10^4 detectors, each attached to its own lock-in [illegible]. Such is the goal of the present work.

1. P. Chavel and S. Lowenthal, J. Opt. Soc. Am. [illegible], [illegible] ([illegible]).

The basic idea is to exploit a widely known but little used property of image orthicon television cameras. By varying the target voltage in these cameras, we can alter the amount of charge deposited on the target for a given light intensity. For large accelerating voltages (the usual operating condition), the net charge deposited is large and positive (secondary emission ratio $\delta > 1$). As the accelerating voltage is reduced, the charge deposited is reduced until it finally goes through zero and becomes negative ($\delta < 1$). Thus the orthicon can be a bipolar image detector. To make use of this property in a noncoherent optical processor, we proposed to temporally modulate the pupil function of the system with an electro-optic or acousto-optic modulator in such a way that the system point spread function is the positive part of the desired bipolar filter function during one half-cycle of the modulation, and the negative part during the other half-cycle. The input data (for example, from a CRT or photographic transparency) are in the object plane of this optical system, and the filtered data appear in the image plane where the orthicon is located. The accelerating voltage of the orthicon is switched between the $\delta < 1$ and $\delta > 1$ conditions in synchronism with the pupil modulation. Thus each element of the orthicon target is accumulating negative charge while the optical system is switched to the negative part of the filter function, and positive charge for the positive part. In brief, each element independently performs as an optical detector and synchronous demodulator. Since an orthicon has about 1000×1000 resolvable elements, it is the functional equivalent of a million lock in amplifiers.

QUANTUM OPTICS AND LASER PHYSICS

(M. O. Scully, S. Zubairy, G. Moore)

Objectives

Quantum optics and laser physics research in the areas of general relativity, laser spectroscopy, quantum theory of radiation, heterodyne detection, photon statistics, and quantum nondemolition measurements.

Progress

In the area of the theoretical study of proposed tests of general relativity, we have proposed an optical test employing an earthbound ring laser interferometry to test metric theories of gravitation. The proposed test would be sensitive to a preferred frame in the universe, to the geodetic precession, and to the Lense-Thirring effect.

We have made theoretical studies on new techniques for achieving resolution beyond the natural linewidth, limited by the difference between the decay rates rather than their sum. These techniques provide the possibility of enhanced spectral resolution, as well as giving a direct measurement of the difference between the decay rates.

We have studied quantum beat phenomena to elucidate the internal consistency of semiclassical radiation theories. A simple example is a case in which the results of a self-consistent fully quantized calculation differ substantially from those obtained by means of a semiclassical theory even when augmented by the notion of vacuum fluctuations.

We investigated the noise limitations in the optical heterodyne detection. We conclude that an improvement over the present shot noise limit can be made if a light source whose photon distribution function is narrower than Poissonian is employed as a local oscillator. We studied the photon statistics in multiphoton absorption and emission processes and obtained exact solutions for the reduced density matrix of the field. We have shown that the photon statistics leads to the possibility of observing antibunching in multiphoton absorption process.

Other groups working in the detection of gravitational radiation have recently proposed new measurement techniques, and these techniques may have applications in quantum optics. We have investigated the effects of quantum noise in measurements of this type.

Publications and Interactions

M. O. Scully, "Suggestion and analysis for a new optical test of general relativity," in H. Walther and K. W. Rothe (eds.), Laser Spectroscopy IV, Springer-Verlag, 1979, p. 21.

M. O. Scully, "On quantum beat phenomena and the internal consistency of semiclassical radiation theories," in A. O. Barut (ed.), Foundations of Radiation Theory and Quantum Electrodynamics, Plenum, 1980, p. 45.

M. P. Haugan, M. O. Scully, and K. Just, "A proposed optical test of preferred frame cosmologies," Phys. Lett. 77A: 88, 1980.

P. Meystre, M. O. Scully, and H. Walther, "Transient line narrowing: A laser spectroscopic technique yielding resolution beyond the natural linewidth," Optics Commun. 33(2): 153-157, May 1980.

M. S. Zubairy and J. J. Yeh, "Photon statistics in multiphoton absorption and emission processes," Phys. Rev. A 21: 2696, 1980.

P. Meystre, H. Walther, and M. O. Scully, "Transient line narrowing: Laser spectroscopic technique yielding resolution beyond the natural linewidth" (invited paper), Eleventh International Quantum Electronics Conference, Boston, Mass., June 23-26, 1980; abstract in J. Opt. Soc. Am. 70(6): 579-580, June 1980.

M. O. Scully, M. S. Zubairy, and M. P. Haugan, "Cosmologically preferred frame and Sagnac interferometry," presented at Eleventh International Quantum Electronics Conference, Boston, Mass., June 23-26, 1980; abstract in J. Opt. Soc. Am. 70(6): 618-619, June 1980.

M. P. Haugan, M. O. Scully, and M. S. Zubairy, "A proposed optical test of metric gravitation theories," presented at 9th International Conference on General Relativity and Gravitation, Jena, East Germany, July 14-19, 1980.

M. S. Zubairy, "How to beat photon noise in heterodyne detection," presented at Workshop on Interface Between General Relativity and Quantum Optics," Garching, West Germany, July 21-25, 1980.

M. Hillery, "Quantum noise in quantum nondemolition measurements," presented at Workshop on Interface Between General Relativity and Quantum Optics," Garching, West Germany, July 21-25, 1980.

Professional Personnel Associated with This Effort

M. O. Scully, Professor
Gerry Moore
S. Zubairy
M. Hillery
J. Small
P. Goode
H.-W. Lee

INTERFEROMETRIC MEASUREMENTS OF DISPERSION IN OPTICAL FIBER WAVEGUIDES

(J. J. Burke, W. D. Bomberger)

Objective

Our objective this year was to demonstrate the validity of a new idea in fiber measurement: that pulse broadening in a single-mode fiber can be measured without broadband electronics and with fibers whose lengths are less than 1 meter.

Progress

We are pleased to report that this objective has been met. A pulse broadening of 77 picoseconds per kilometer of fiber length per nanometer of source bandwidth was measured with a cw GaAlAs laser diode (λ = 0.87 μm), coupled to a single-mode borosilicate fiber 20 cm long. For comparison we note that the prior art required fiber lengths of 1 km or more and electronics with gigahertz bandwidth. Our electronics had only 1 kHz bandwidth.

During the fall of 1979 we ordered the components of the scanning interferometer we had designed and the stable table that supports it. By early spring of 1980, all the parts had been received and were assembled. Initial attempts to demonstrate the principle with the use of a filtered xenon are at visible wavelengths were not definitive. The signal levels were too small, and the available fibers supported more than one mode. We therefore switched to a laser diode source that provided ample signal strengths at a wavelength where the fibers were single mode. The expected results were soon manifest, though the complicated power spectrum of the laser source, operating close to threshold, made detailed interpretation of the interferograms difficult. As indicated above, we have now completed the initial phase of interpretation, and are accordingly able to measure the quantities that govern pulse broadening. The interferograms contain much additional information about the power spectrum of the laser source and the frequency response of the fiber. Not only are pulses broadened, but their shape can change dramatically. We are now exploring digital techniques for acquiring and analyzing the interferograms. We anticipate that we will ultimately be able to completely characterize the effective refractive index of a single-mode fiber at any frequency of interest, even in the "zero dispersion" region near 1.37 μm, where conventional measurements are extremely difficult.

Publications and Interactions

We are preparing a formation publication of this work, anticipating submission to the Journal of the Optical Society of America. In addition, this work was the substance of Dr. Bomberger's recently completed doctoral dissertation (see Degrees Awarded, below).

Dr. Bomberger presented a paper on this work at the Annual Meeting of the Optical Society in Chicago on October 15. Dr. Burke gave a similar paper at the Symposium on Optical Fiber Measurements in Boulder, Colorado (NBS), on October 29.

We anticipate that this work will substantially influence the efforts of others in the field of fiber characterization. Dr. Kenneth White of the British Post Office has telexed his desire to visit our laboratory, and at the meeting in Boulder, mentioned above, he discussed the work at length with Dr. Burke.

Professional Personnel Associated with This Effort

J. J. Burke
W. D. Bomberger

Degrees Awarded

William Bomberger, PhD (Optics)
Dissertation title: "Interferometric Measurement of Dispersion in Optical Fibers"

EVAPORATED THIN FILM LENS SYSTEMS FOR INTEGRATED OPTICS

(O. N. Stavroudis, A. F. Turner)

Objectives

This is the third in a series of year-long studies to provide the background needed to design and make thin-film components for integrated optical (IO) circuits. The emphasis has been on multilayer waveguides and on refracting elements to be used with them, in particular on aspheric thin film lenses with elliptical contours. The goal is to understand the behavior of multilayer thin film waveguides and to take advantage of their special characteristics to solve geometrical optical problems of IO circuitry. This year our objectives were as follows:

1. To demonstrate the advantages in integrated optics of multilayer guides with silver cladding.

2. To devise methods of making masks or stencils capable of producing lenses consisting of deposits with elliptical contours, as required by theoretical designs, and of studying the lenses so produced.

3. To construct and install equipment in one of the coaters, for the purpose of bombarding with electrons the substrate and film during deposition, in an effort to produce an essentially amorphous film structure with reduced scattering losses.

4. To complete a set of computer programs needed in the design of multilayer waveguides as well as in the analysis of experimental data.

5. To write computer programs for tolerancing previous designs of aspheric beam-expanding/collimator lenses.

6. To design Fourier transform thin film lenses to be used in conjunction with the above collimators.

Progress

The first phases of objective 1 were reported in a paper read by G. Al-Jumaily at the Optical Society of America meeting on June 3, 1980; a paper is being prepared for publication. The first mask of objective 2 has been fabricated and used to make several beam-expanding/collimator thin film lenses, on which ray path studies have been begun. The equipment described under objective 3 is operational, ready for sample preparation and study. Objectives 4 and 5 have been completed. The lenses of objective 6 are in the design stages.

1. Silver-Clad Waveguides. We have shown, both theoretically and experimentally, that the losses incurred by cladding a waveguide with silver can be reduced substantially by inserting layers that enhance the reflectance of the silver.

The range of mode indices of a waveguide can be extended downward by depositing the guide on an opaque metal film. Such an extension is desirable in the design of IO lenses and prisms. But even if silver is used for the cladding, the guide becomes excessively lossy, particularly toward the lower values of mode indices. Low incices are crucial for the interconnecting waveguide on which the optical components of an IO circuit will be deposited. The losses can be greatly reduced by introducing reflection-enhancing additional layers; in the present work this has resulted in a six-film structure. Its dispersion curves, however, have regions of extreme distortion. As we attempted to explain this behavior it became more and more apparent that the electric field distribution within the structure must be given major consideration. Some progress has been made toward qualitative explanations along these lines.

One of the simplest designs of a low-loss silver-clad waveguide was selected for extensive study with both numerical calculations and experimental verification on many samples. All of the samples were made with standard vacuum evaporation methods. The design is:

$$Ag|2L(1.5H)2L|W|P|A$$

where
- Ag = opaque silver film
- L = quarterwave film of chiolite, $n = 1.35$
- H = quarterwave film of Sb_2O_3, $n = 2.1$
- W = waveguide layer of evaporated glass, $n = 1.66$, approximately 2 quarterwaves thick
- P = film of Sb_2O_3, of variable thickness to correspond to a patch optical component (for example, a lens) deposited on the guiding structure
- A = air.

In all cases, the reference wavelength is $\lambda_0 = 0.633$ µm (He-Ne laser radiation).

The $|2L(1.5H)2L|$ unit enhances the reflectance of the silver over a very wide angular (mode index) range, thereby reducing the losses otherwise incurred by the presence of the silver. Experimentally one measures losses reduced to 10 dB/cm for mode indices as low as 1.5.

2. Production of Aspheric Thin Film Lenses by Vacuum Evaporation Through a Mask. Several beam-expanding/collimator lenses have been deposited on evaporated glass waveguides. The lenses consist of thin

films of Sb_2O_3 evaporated through the mechanical mask, which produced elliptical contoured "surfaces." The performance of these lenses has been examined, and thus far the ray paths through them appear to agree with those calculated. It is now clear that an in-depth experimental ray trace study will require better masks; these are now in the design stages and will involve a major effort.

3. Electron Bombardment. Bombardment of the substrate with electrons during film deposition shows promise of producing a finer grained, or even amorphous, film. This in turn should reduce the light scattering losses in a film--an important factor in waveguide technology where there is now a paucity of evaporable film materials that yield low-scatter, low-loss films. Whereas the amorphous evaporated glass films that we are using have acceptably low losses of 1 dB/cm or less, the other two materials, Sb_2O_3 and chiolite, are only marginally useful because of scattering. The electron bombardment method should help correct this situation and increase the choice of evaporable materials suitable for thin-film waveguide applications. Although the technique was invented 33 years ago and has been in limited commercial use, no systematic studies on it have been reported in the literature.

To carry out the technique, we have installed auxiliary equipment in the 18-inch coater. A 10-inch-diameter loop of tungsten wire located midway between the resistance-heated vapor sources and the substrate holders serves as the electron emitter. It is heated by 12-V ac well insulated transformers and held at several kV negative with respect to the grounded substrate holders.

Preliminary observations indicate that chiolote films show less scattering when the bombardment is employed. In the future, special attention will also be given to films of zinc sulfide and mixed fluorides such as potassium hexafluorozirconate.

4-5. Generalized Waveguide Analysis. Objectives 4 and 5 have been completed. In particular, borrowing from certain mathematical concepts familiar in quantum optics, we have developed a novel method of analyzing a generalized multilayer waveguide structure for its allowed modes. The method is expecially well adapted to numerical computer calculations. A manuscript describing the method (S. A. Shakir and A. F. Turner) has been submitted to Applied Optics for publication.

6. Fourier Transform Lens Design. The beam-expanding/collimator lenses of objective 2 are intended to be used in conjunction with a thin-film Fourier transform lens, in configurations such as are being studied elsewhere for integrated optical RF spectrum analyzers. Fourier lens designs for present purposes have been begun.

JSOP support for the above-described studies was terminated on September 30.

Publications and Interactions

A. F. Turner and S. D. Browning, "Refracting boundaries in thin film lightguides," SPIE, Aug. 27-28, 1979, San Diego, Calif.; Proc. SPIE 204: 53, 1979.

S. A. Shakir and A. F. Turner, "Method of poles for multilayer thin film waveguides," submitted to Applied Optics.

A. F. Turner and G. Al-Jumaily, "Low-loss Ag-clad thin film waveguides for integrated optics," paper TuAA10, Optical Society of America 1980 Spring Conference on Applied Optics, Mills College, Oakland, Calif., May 31-June 6, 1980; paper in preparation for publication.

Professional Personnel Associated with This Effort

O. N. Stavroudis, Professor
A. F. Turner, Professor Emeritus
Ross H. Potoff, thin film specialist
G. Al-Jumaily, graduate student (volunteer)
C.-C. Lee, graduate student
S. A. Shakir, graduate student

PHASE CONJUGATION

(M. Sargent III, R. Shoemaker)

Objective

Our research objectives in the past year have been to study aspects of phase conjugation. Specific work has been in the areas of phase conjugation with a detuned signal and two-photon phase conjugation.

Progress

1. Phase Conjugation with a Detuned Signal. Under JSOP support in January through August 1980, we have used the narrow-band reflection spectrum to predict pulsed-signal operation. The technique is related to the χ^3 phase-conjugation discussions of Yariv et al.[1] and Fisher et al.[2] The pulse is Fourier analyzed, multiplied by the amplitude spectral transmission function, and re-summed, yielding the transmitted pulse. The spectral transmission function is determined from the signal absorption coefficients. At first, this appears to be fraught with difficulty, for we are using Fourier analysis in a nonlinear problem. However, we are considering linear deviations about a steady state that is not in thermal equilibrium. Fourier analysis applies, and we discover information about how the medium attempts to return to thermal equilibrium, namely relaxation times, like T_1 and T_2. The transmission

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1. A. Yariv, D. Fekete, and D. M. Pepper, Opt. Lett. 4: 52, 1979.

2. R. A. Fisher, B. R. Suydam, W. W. Rigrod, and B. J. Feldman, XIth Internat. Quant. Electronics Conf., Boston, June 1980.

functions look simple enough that we may be able to derive analytic formulas for simple pulse shapes, like delta and step functions.

Qualitatively, we can predict the effect of the medium on the transmitted pulse. A delta function signal induces a grating with the help of the pump wave. The cw pump wave then continues to read out this grating for as long as it lasts. The effect is much like a bell: The sound lasts much longer than the blow that created it. Hence the conjugate pulse consists of something looking like the incident signal plus a long pulse with length about equal to T_1. Understanding the response of a medium to a pluse is very important in a number of applications for phase conjugation and specifically with regard to laser-induced fusion. It also provides a new and potentially very important spectroscopic technique.

2. Two-Photon Phase Conjugation. Also under JSOP support, Tao-Yi Fu and Murray Sargent have developed the theory of two-photon phase conjugation. This combines the Abrams-Lind phase conjugation theory[3] with the two-photon theory of Narducci et al.[4] The signal, pumps, and hence the conjugate are all chosen to have the same frequency, and the medium is assumed to be homogeneously broadened. The theory predicts three significant effects that are absent in the two-level medium case: (1) a double-peaked reflection spectrum, (2) a Yariv-Pepper oscillation (infinite reflectivity) condition[5] in an absorber,

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3. R. L. Abrams and R. C. Lind, Opt. Lett. 2, 94 (1978); 3, 205 (1978).
4. L. M. Narducci, W. W. Eidson, P. Furcinitti, and P. C. Eteson, Phys. Rev. A16, 1665 (1977).
5. A. Yariv and D. M. Pepper, Opt. Lett. 1, 16 (1977).

and (3) an unbleachable medium. Effects (1) and (2) result from the presence of a pure-index contribution to the phase-conjugating polarization in addition to a mixed index-absorption contribution. The pure index term results from off-resonant single-photon transitions from levels that are saturated by two-photon transitions. The corresponding phase-conjugation contribution involves an induced grating or hologram as does that in the two-level atom case. The mixed index-absorption contribution dominates at low pump intensities, and results from the conjugated signal interacting with a two-photon coherence term whose pump wave-vector dependence cancels out. Unlike the usual two-level phase conjugation, no population grating is involved in this process. The double-peaked spectrum results from the interference of these two terms: below the effective resonance frequency, they add; above that frequency they subtract, and two peaks occur. Second, the pure-index conjugation term increases the signal-conjugate coupling enough to dominate the absorption and produce coupled-mode oscillation even in an absorbing medium. Third, whereas the two-level reflection coefficient bleaches to zero at large intensities, the Stark-shifted line center of the two-photon case prevents bleaching and leads to an intensity-independent reflectivity at large intensities.

The results of this work have been published in a paper by Fu and Sargent, and the results and their relationships to earlier work in saturation spectroscopy have been summarized by Sargent at an international conference. Efforts are under way at the Optical Sciences Center and elsewhere to see the two-photon predictions experimentally. Theoretical work is continuing under other funding with special emphasis on spectroscopic applications. The pulsed-signal work is being pursued in collaboration with Bob Fisher and Barry Feldman at Los Alamos.

Publications and Interactions

Tao-Yi Fu and M. Sargent III, "Theory of two-photon phase conjugation," Opt. Lett. 5(10): 433-435, Oct. 1980.

M. Sargent III, "Phase conjugation in three, four, and infinite dimensions," presented at ICO Conference on Optics in Four Dimensions, Ensenada, Mexico, August 1980; to be published in the proceedings of that conference.

Professional Personnel Associated with This Effort

M. Sargent III
R. Shoemaker
T.-Y. Fu

MAGNETOSTRICTION

(S. F. Jacobs)

Objective

The magnetostriction studies consist of two parts:

1. A search for <u>any</u> magnetostrictive effect in low expansivity metals (such as ULE, Cer-Vit, Zerodur, and fused silica).

2. A measurement of magnetostriction in Superinvar and Invar.

The former has never been measured; the latter has been measured only at large field strengths.

Progress

The effort during this period has been devoted to the building up of a slave-laser/stable-laser system. In addition, with support from NASA, we have completed construction of a cryostat/sample holder, which will make possible measurement at temperatures approaching that of liquid helium. The slave laser that is nearing completion is based on a modification of an inexpensive commercial laser, which was reported by T. Baer et al.[1] We have improved slightly on their transducer performance, by using tubular PZT-5H, and we expect now to be able to fabricate our own frequency-stabilized lasers, as well as the slave laser, through use of this new development.

Another area of progress is the installation of the Hewlett Packard Model 85F computer/controller that will automate our measurement

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1. T. Baer, F. V. Kowalski, and J. L. Hall, Appl. Opt. 19: 3173, 1980.

procedure. This work was made possible by support from the Itek Corporation.

Professional Personnel Associated with This Effort

S. F. Jacobs, Professor

Further Information (Background)

Figure 1 shows the magnetostriction measurements that had been made previously: No such effects have been measured in low-expansivity nonmetals, and magnetostriction effects in Superinvar and Invar have been measured only at large field strengths.

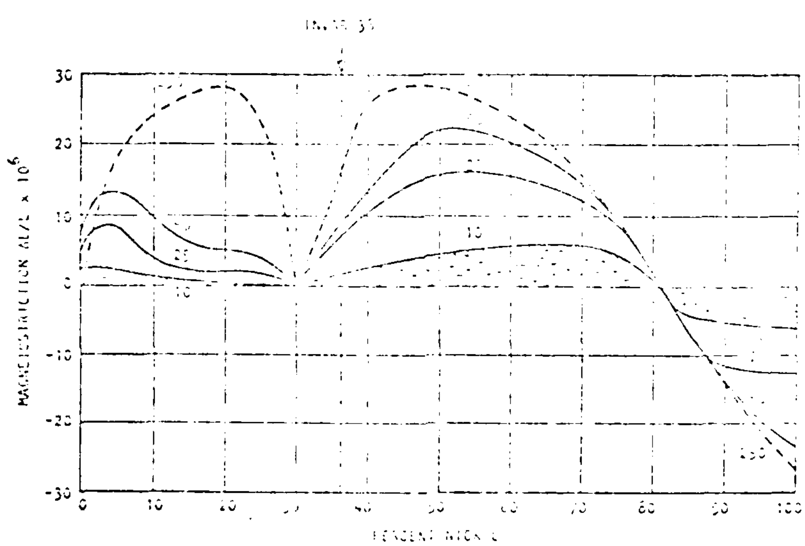

Fig. 1. Longitudinal Magnetostriction in Iron-Nickel Alloys for Various H (in Oersteds) (after Schulze).

Figure 2 shows the arrangement we are constructing. Its sensitivity (for objective 1) should be better than 10^{-12} cm, or $\Delta L/L < 10^{-13}$, which is the expected seismic background vibration level.

It is planned first to perform the low-sensitivity ($\Delta L/L \approx 10^{-9}$) Invar measurements by introducing dc magnetic fields. Later we will use an alternating magnetic field and narrowband phase-sensitive detection to look for magnetostriction in nonmetals.

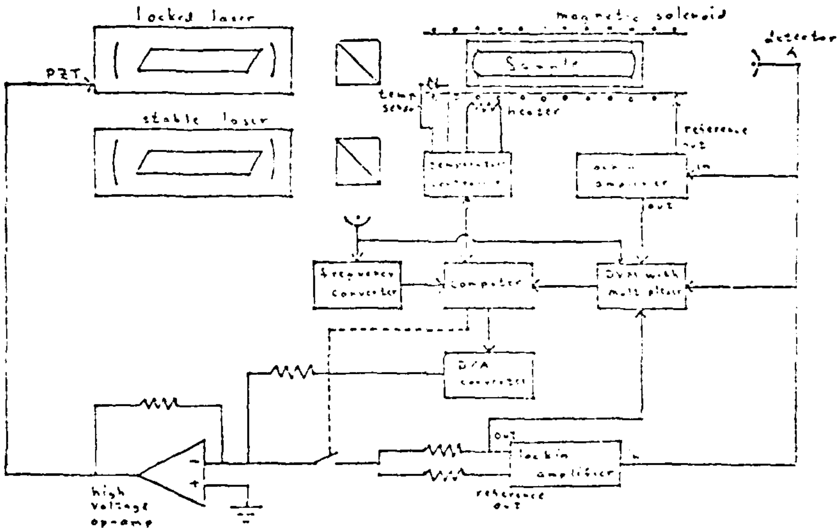

Fig. 2. Magnetostriction Measurement Setup.

USE OF HAC DISCHARGE TUBE TO STUDY CHARGE-TRANSFER INTERACTIONS

(F. Hopf)

Objective

Our objective has been to determine whether a hollow-anode, hollow-cathode (HAC) discharge tube[1] could be used as a quick and easy way of studying charge-transfer interactions.

Progress

The HAC is a modification of the hollow-cathode discharge (HCD). An HCD has the property that the voltage saturates[2] at about 100 to 300 V, so it is limited both in electron and ion energies. The HAC is a hybrid between an HCD and an electron-beam and allows for voltages that, in practice, have exceeded 2000 V. This gives higher electron and ion energies with improved spattering yield for metal-vapor lasers and higher excitation energy for improved laser action at short wavelengths. In addition, the discharge volume of the HAC is physically separate from the high-voltage volume and is largely free of stray fields. Hence the Stark shifts are relatively small.

We tried three HAC discharge tubes that spanned the stated parameter ranges of the device, but we were unable to achieve true HAC performance. Our results were intermediate between HAC and HCD, as our voltages saturated near 100 V; the results were largely the same

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[1]K. Rozsa, M. Janossy, L. Csillag, and J. Bergou, Phys. Lett. 63A: 231, 1977.

[2]K. Rozsa, KFKI 1975-63, p. 5, and KFKI 1980-08, p. 16.

regardless of the tube used. Clearly, there is some element of operation that we have not been able to identify, but we can conclude that HAC is not as straightforward a device as the literature would suggest.

Professional Personnel Associated with This Effort

F. A. Hopf, Professor

MULTIPHOTON LASER EXCITATION OF SINGLE ELECTRON ATOMS

(W. E. Lamb, Jr.)

Objective

The objective of this study is to develop a computer program to integrate the quantum mechanical time-dependent Schrödinger wave equation for a one-electron atom in the presence of a very strong field.

Progress

The work for the reporting period was devoted to writing programs for use on the Data General ECLIPSE S230 computer. These programs will calculate the energy transfer to the atom and the probabilities of excitation and ionization as a function of time. The parameters to be varied will include laser intensity, frequency, type of polarization, and degree of coherence of the radiation. Also, the induced dipole moment of the atom and its Fourier components will make it possible to study the conditions for efficient generation of very high harmonic radiation by an atomic frequency multiplier. The results of the calculations will be displayed as interactive graphs. Exploratory runs have been made and are promising.

Publications and Interactions

An account of the projected work and status was presented to the Joint Services visiting committee in October 1980.

Professional Personnel Associated with This Effort

Willis E. Lamb, Jr., Principal Investigator
Milivoj Belic, Post-Doctoral Research Associate

Invention Disclosure

No invention or patent disclosures have been made. The potential application of the work is to the generation of very high laser harmonics, but it is in too early a stage to judge the outcome. The method does not seem to have been used by other workers in the field of multiphoton ionization processes.

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